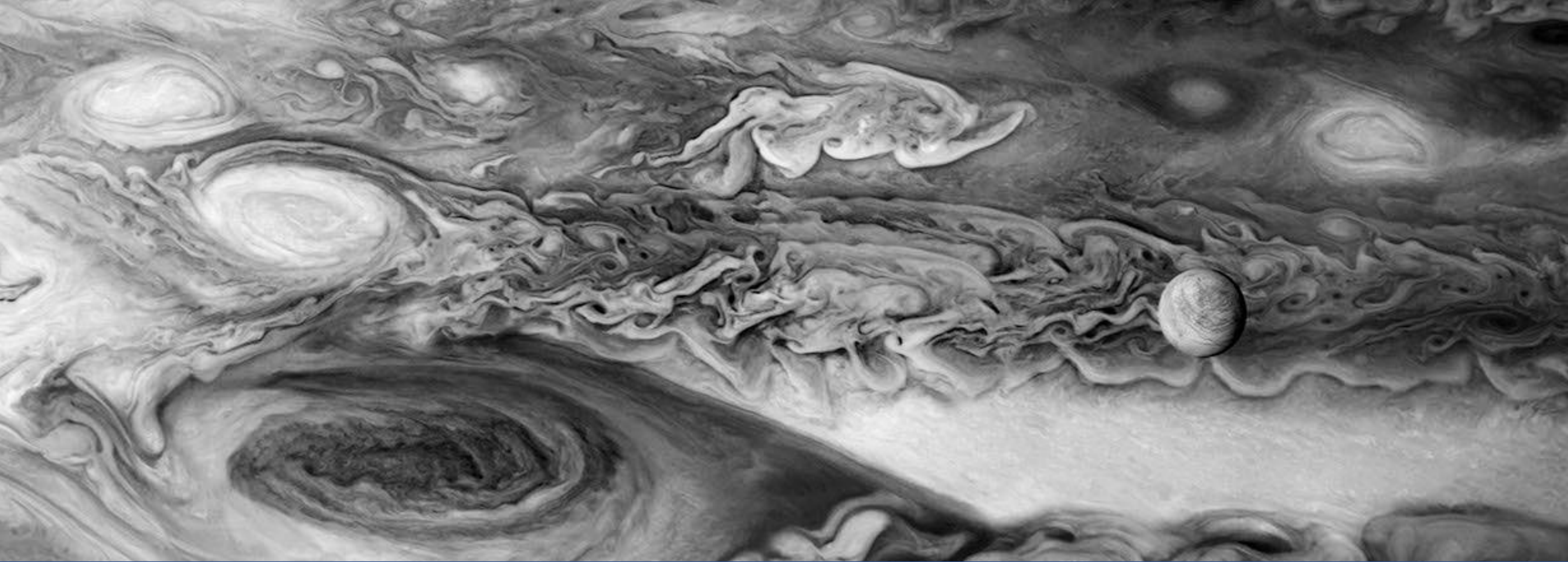

Modeling the Probability of Contaminating Europa

Mike DiNicola (Today's Presenter)

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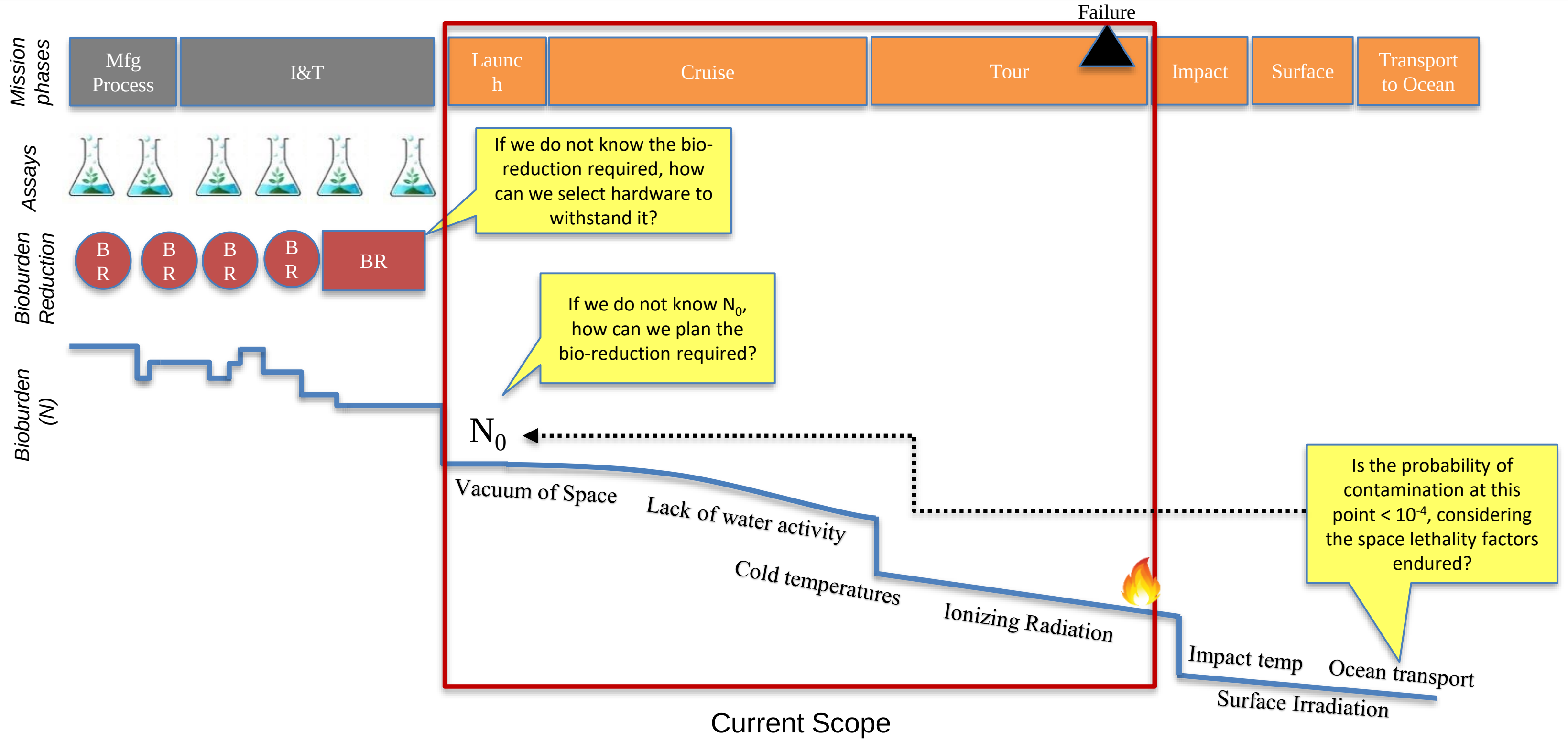
Jet Propulsion Laboratory, California Institute of Technology

Tonight's Discussion

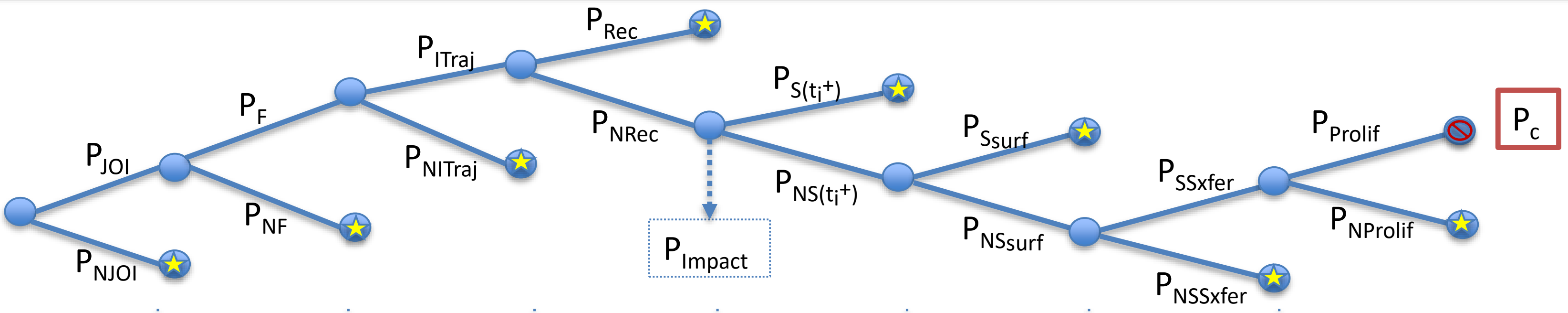
- Motivation for the Model
- Contamination Probability Event Tree
- Bio-regions: What are They?
- Explore the Math Model
- Illustrations & Examples

Motivation

NPR 8020.12D: "The probability of inadvertent contamination of an ocean or other liquid water body must be less than $1x10^{-4}$ per mission"



Contamination Probability Event Tree



P_{NJOI}= probability JOI is not achieved

Europa contam-ination cannot occur if there is a failure pre-JOI

P_{NF}= probability no failure prevents deorbit burn

Considers post-JOI non-recoverable maneuver failures (e.g. operations, s/c hardware, micrometeroid)

Considers recoverable maneuver failures

P_{NITraj} = probability not on an impact trajectory at failure

Considers each maneuver's covariance matrix to calculate probability on impact trajectory

P_{Rec} = probability of recovering prior to impact

Recoverable failure downtime distribution considered

$P_{S(t_i^+)}$ = probability sterile post-impact

Considers cruise/tour radiation exposure over all s/c surfaces

Organism survivability in space (vacuum, water activity, temp)

Considers impact temp (velocity, angle)

P_{Ssurf}= probability sterilized by surface irradiation

Considers s/c breakup analysis and burial depths

Considers impact site and exposure time on surface

$P_{NSSxfer}$= probability of no transfer of contamination to subsurface

Considers impact site geologic activity

Considers subsurface transfer mechanisms

$P_{NProlif}$= probability of no survival/ proliferation in ocean

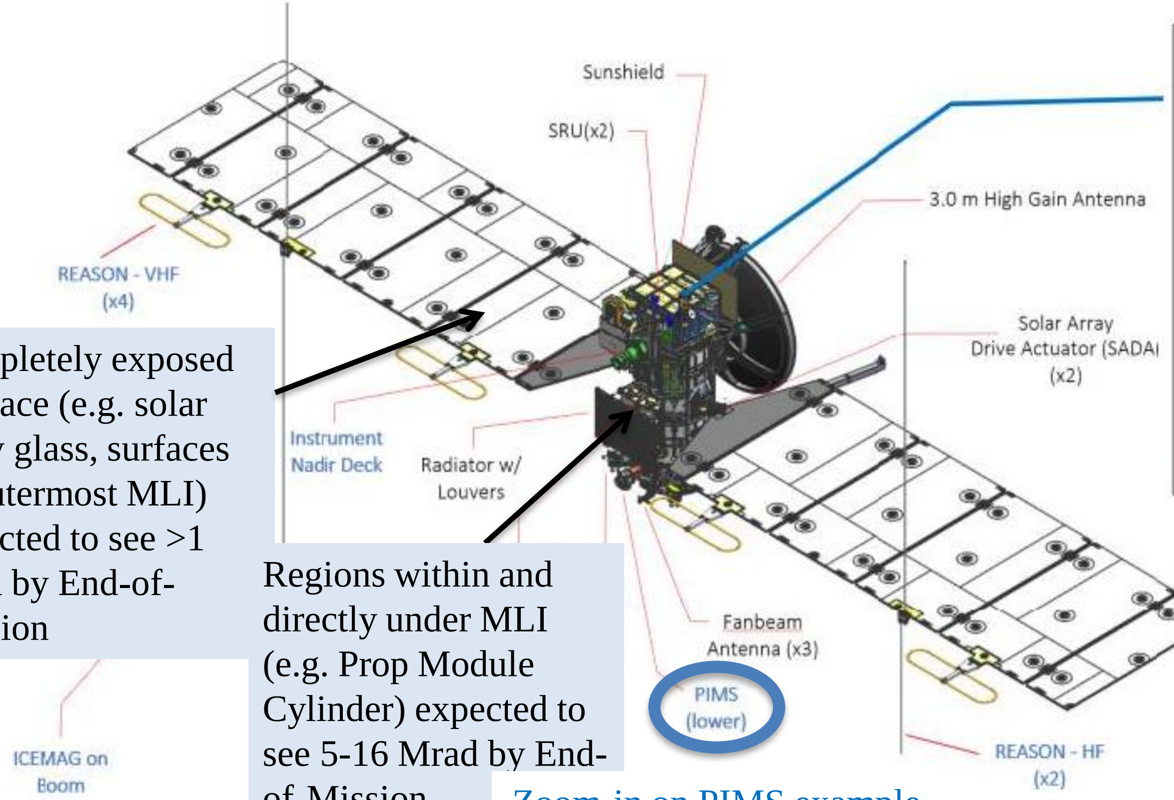
Considers ocean conditions (nutrients, energy, reproduction)

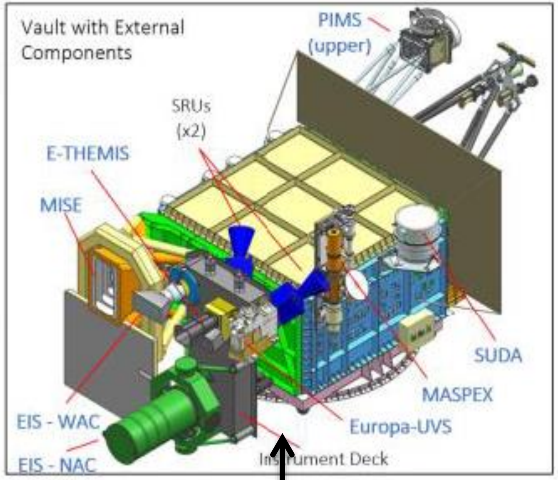
KEY

Definition	Analysis complete	Allowable Analysis	PP credit uncertain

Bio-region Overview

Bio-region: Areas of the spacecraft experiencing a similar environment in terms of organism viability





Completely exposed to space (e.g. solar array glass, surfaces of outermost MLI) expected to see >1 Grad by End-of-Mission

Regions within and directly under MLI (e.g. Prop Module Cylinder) expected to see 5-16 Mrad by End-of-Mission

Highly shielded components in the vault: very low radiation exposure (as low as 20 krad by End-of-Mission), temperature controlled, some components hermetically sealed.

Zoom-in on PIMS example

Mathematical Formulation

Probability of impacting Europa when the n^{th} maneuver fails & no recovery

M_n= # of trajectories (of 20k-100k per maneuver) resulting in impact if maneuver ***n*** fails without recovery

# of bio-regions **j** (25)

Probability one or more organisms survive to contaminate Europa, given impact occurs when the n^{th} maneuver fails and the initial bio-burden at launch

Probability any individual organism of group ***k***, in bio-region ***j***, surviving

Sum over all ***N*** (163) maneuvers

Probability of Europa Contamination

$$P_C = \sum_{n=1}^{N} \Pr\left(I_n\right)\left[1-\frac{1}{M_n}\sum_{m=1}^{M_n}\prod_{j=1}^{J}\prod_{k=1}^{4}\left(1-s_{j,k,m,n}\right)^{N_{0,j,k}}\right]$$

Goal: "Solve" for initial bio-burden at launch, $N_{0,j,k}$

Organism groups ***k*** = 1, 2, 3, 4.

*If $\Pr\left(I_n\right) = 0$, then $\Pr\left(I_n\right)\left[1-\frac{1}{M_n}\sum_{m=1}^{M_n}\prod_{j=1}^{J}\prod_{k=1}^{4}\left(1-s_{j,k,m,n}\right)^{N_{0,j,k}}\right] = 0$

Brief Derivation

The probability that an **individual** group *k* organism launched with the Clipper spacecraft survives in bio-region *j* when impact occurs on trajectory *m* after failing to complete maneuver *n*. → $s_{j,k,m,n}$

The probability that this individual organism dies… $\left(1 - s_{j,k,m,n}\right)$

The probability that **all** of the group *k* organisms in bio-region *j* die… $\left(1 - s_{j,k,m,n}\right)^{N_{0,j,k}}$

The probability that all organisms across the entire spacecraft die… $\prod_{j=1}^{J}\prod_{k=1}^{4}\left(1 - s_{j,k,m,n}\right)^{N_{0,j,k}}$

Assume Clipper has failed to complete the n^{th} maneuver of its tour and is now on a fixed trajectory, *m*, that will impact Europa.

The probability all organisms die when Clipper fails to complete the n^{th} maneuver and impacts Europa.

$$\frac{1}{M_n}\sum_{m=1}^{M_n}\prod_{j=1}^{J}\prod_{k=1}^{4}\left(1 - s_{j,k,m,n}\right)^{N_{0,j,k}}$$

Sum over all ways Clipper can impact Europa when it fails to complete the n^{th} maneuver

The probability **some organism lives** when Clipper fails to complete the n^{th} maneuver and impacts Europa.

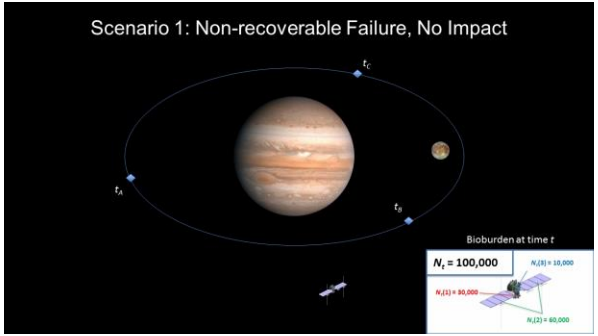
$$1-\frac{1}{M_n}\sum_{m=1}^{M_n}\prod_{j=1}^{J}\prod_{k=1}^{4}\left(1 - s_{j,k,m,n}\right)^{N_{0,j,k}}$$

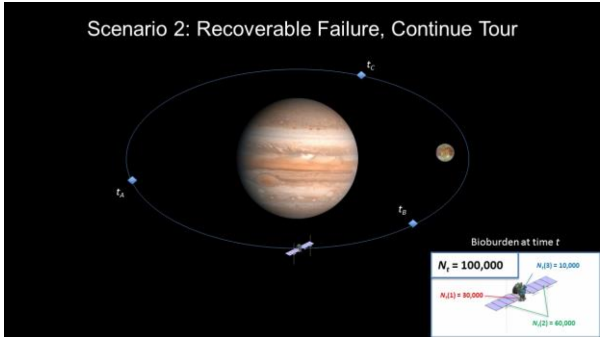
The probability some organism contaminates Europa.

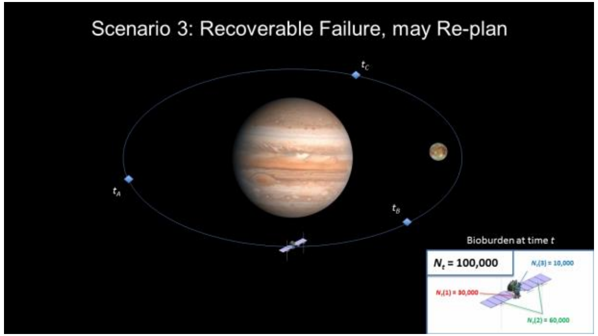
$$P_C = \sum_{n=1}^{N}\Pr\left(I_n\right)\left[1-\frac{1}{M_n}\sum_{m=1}^{M_n}\prod_{j=1}^{J}\prod_{k=1}^{4}\left(1 - s_{j,k,m,n}\right)^{N_{0,j,k}}\right]$$

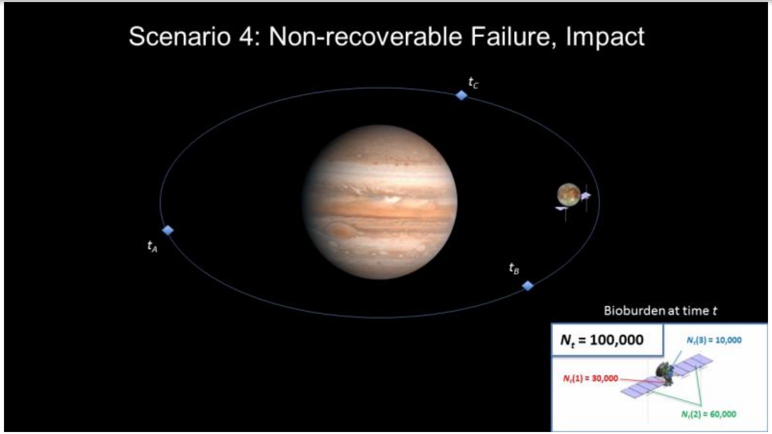
Sum contamination events (i.e. Clipper impacts & some organism lives) over all maneuvers

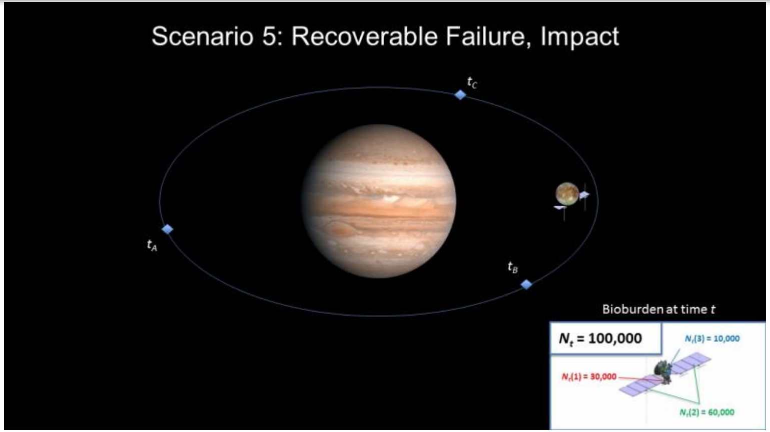
Model Scenarios











P_c is calculated based on these scenarios

The PP Requirement is more Stringent than it May Appear

NPR 8020.12D: "The probability of inadvertent contamination of an ocean or other liquid water body must be less than 1×10^{-4} per mission"

"the introduction of a single viable terrestrial microorganism into a liquid-water environment"

The stringency of this requirement is driven by one or more viable organisms defining a contamination event.

Illustration to follow…

An Illustration

NPR 8020.12D: "The probability of inadvertent contamination of an ocean or other liquid water body must be less than 1x10^{-4} per mission"

"the introduction of a single viable terrestrial microorganism into a liquid-water environment"

Pr[Organism Survives]

Suppose we believe the chances an organism survives to contaminate Europa is really low… like one in a million*

$$s = s_{j,k,m,n} = 1\times10^{-6}$$

Pr[Organism Dies]

The probability this organism dies is almost 1 … no worries about contamination, **right?**

$$1-s = 9.99999\times10^{-1}$$

Pr[All Organisms Die]

Wrong. Consider the fact that there are a **lot** of organisms; for Clipper, typically $N_{0,j,k}$ is from 10^8 to10^{12}.

$$(1-s)^{N_{0,j,k}} = \varepsilon_{j,k} \approx 0$$

$$\Rightarrow \prod_{j=1}^{J}\prod_{k=1}^{4}(1-s)^{N_{0,j,k}}$$

$$= \prod_{j=1}^{J}\prod_{k=1}^{4}\varepsilon_{j,k} = \varepsilon' \approx 0$$

P_C = Pr[Contamination]

So, even when the probability of organism survival is very low, reducing P_C below the Probability of Impact can be very difficult

$$P_C = \sum_{n=1}^{N}\Pr(I_n)\left[1-\frac{1}{M_n}\sum_{m=1}^{M_n}\prod_{j=1}^{J}\prod_{k=1}^{4}(1-s)^{N_{0,j,k}}\right]$$

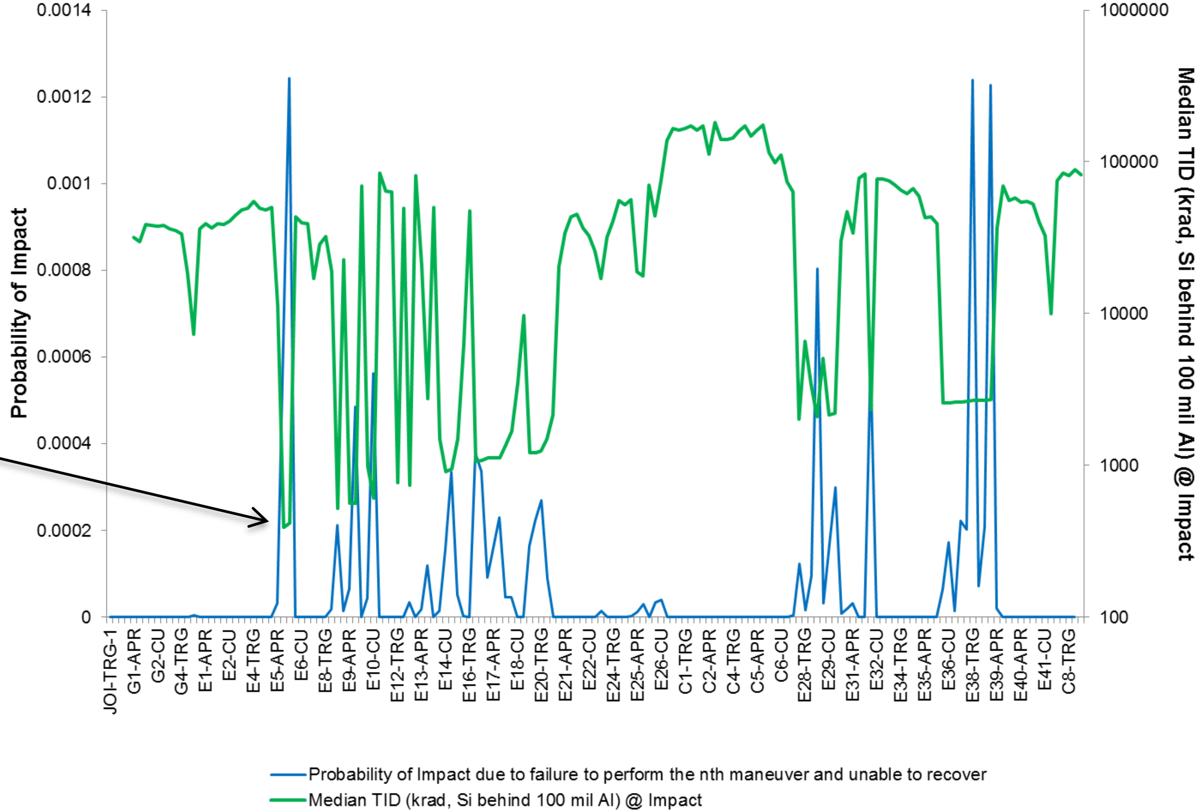
$$= \sum_{n=1}^{N}\Pr(I_n)\,[1-\varepsilon']$$

$$\approx \sum_{n=1}^{N}\Pr(I_n) = \text{Probability of Impact}$$

*For simplicity in this example, assume the survival probability of an organism is the same for all organism groups, bio-regions and impact trajectories.

Low TIDs at Impact Increase the Survival Probability

Note lower TIDs at maneuvers more likely to impact

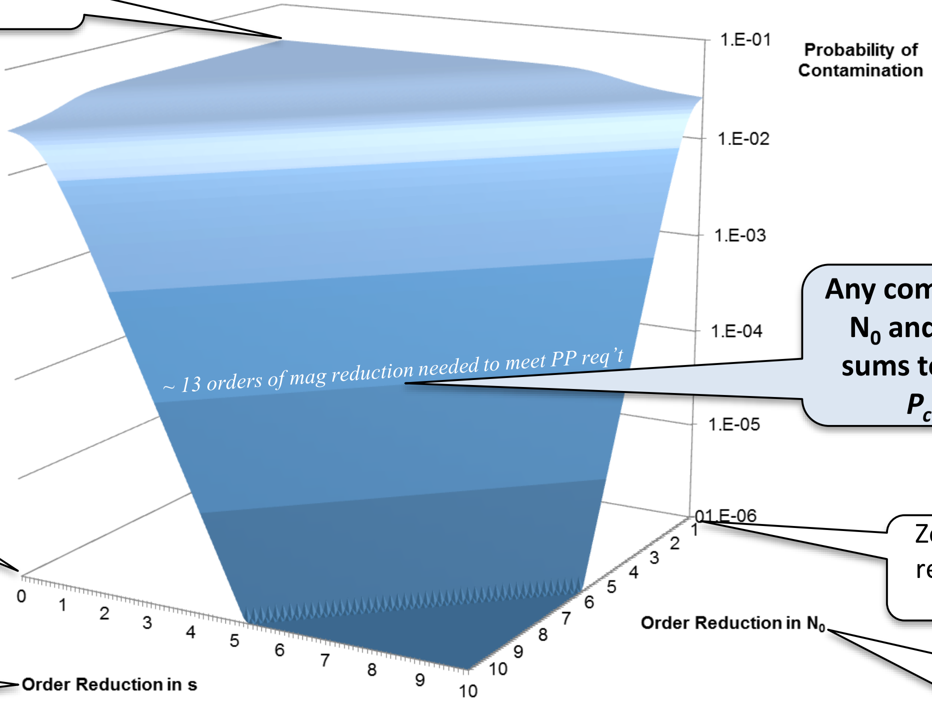


Trajectory 15F10

Sensitivity of P_C to Organism Survival (*s*) and Bioburden at Launch (N_0)

P_C = Probability of Impact

A combination of pre-launch bioburden reduction and credit for additional branches in the Event Tree are needed to satisfy the PP requirement.



Any combination of N_0 and 's' which sums to 13 yields $P_c < 10^{-4}$

Zero on this axis represents the value of 's' through the moment before impact

Zero on this bottom axis represents "cleanroom" N_0 scenario

Reductions in 's' come from impact temperatures, and, if allowed, surface irradiation

Reductions in 'N_0' come from pre-launch microbial reduction, cleaning/assays, etc.

Summing-up & Future Work

- We have an end-to-end probabilistic model architecture to assess the probability of contaminating Europa, as well as other Icy Bodies

- Results to-date show that satisfying the PP Requirement can be non-trivial.

- Currently wrapping-up impact heating analysis and exploring surface/sub-surface transfer portions of the Event Tree

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- Ray Ellyin (Planetary Protection Engineering)

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QUESTIONS?

Back-up

- References
- Bioburden (at-launch) Required to Satisfy PP Req’t, by Radiation Bio-region
- Comparison with Coleman-Sagan
- Clipper Bioburden by Bio-region
- Model Network Diagram
- Foundational Analysis (Reliability, Impact Probability Assessment, Biology)
- Maturity of Input Products to Model
- Additional Bio-region Material
- Alternative Mathematical Derivation
- Summary of Model Features

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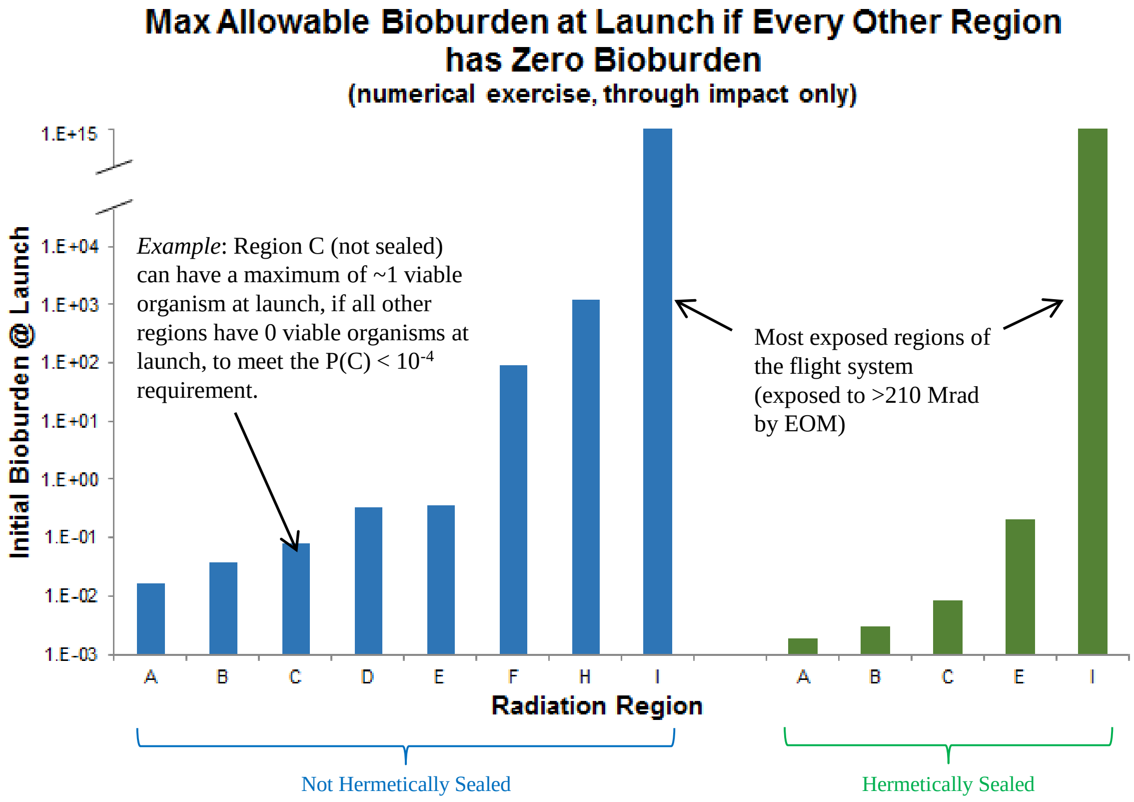
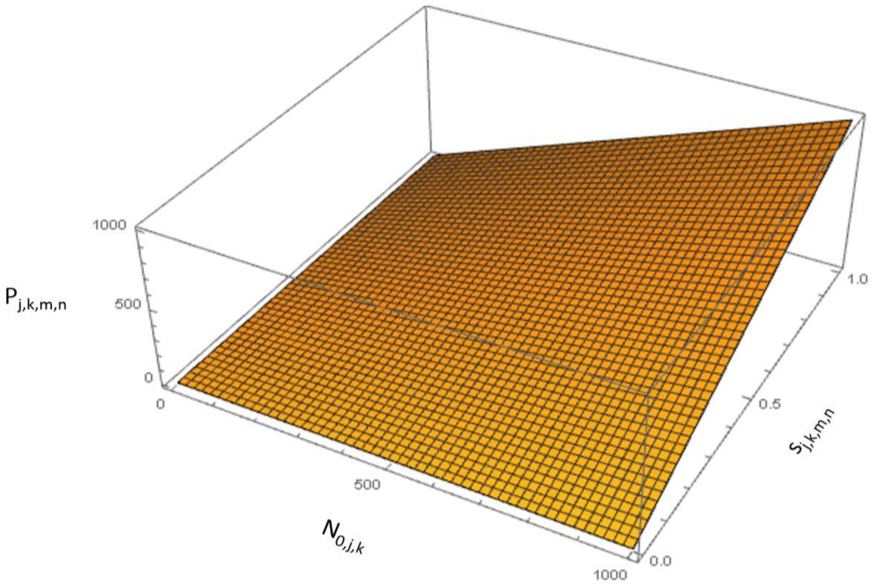
Less than one viable organism is needed in many bio-regions in order to meet P_C requirement

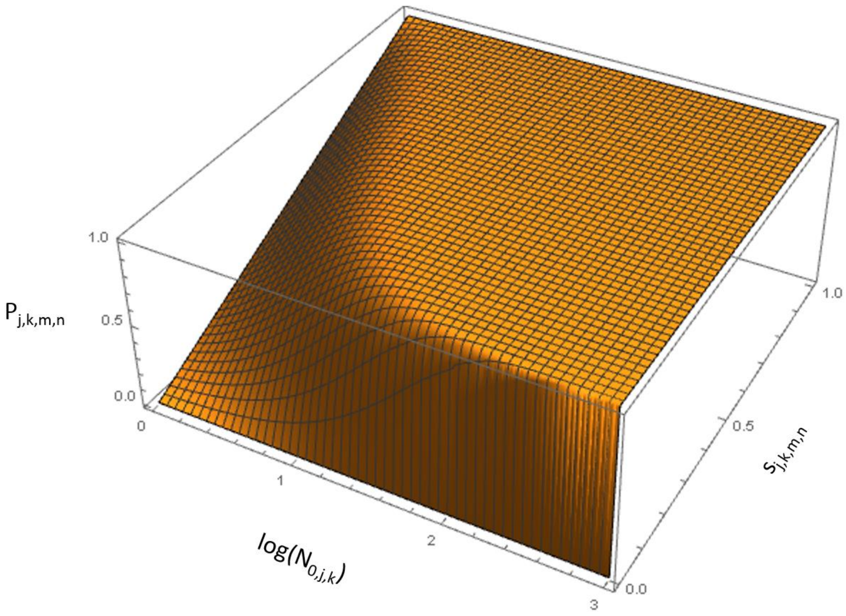
Radiation Bio-regions (rad shown is est. TID by EOM, Si target)
A: < 50 krad
B: ≥ 50 & < 150 krad
C: ≥ 150 krad & < 500 krad
D: ≥ 500 krad & < 1 Mrad
E: ≥ 1 Mrad & < 5 Mrad
F: ≥ 5 Mrad & < 10 Mrad
G: ≥ 10 Mrad & < 16 Mrad
H: ≥ 16 Mrad & < 210 Mrad
I: ≥ 210 Mrad



Comparison with Coleman-Sagan



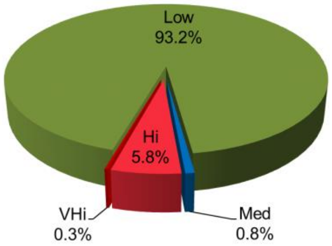
Coleman-Sagan

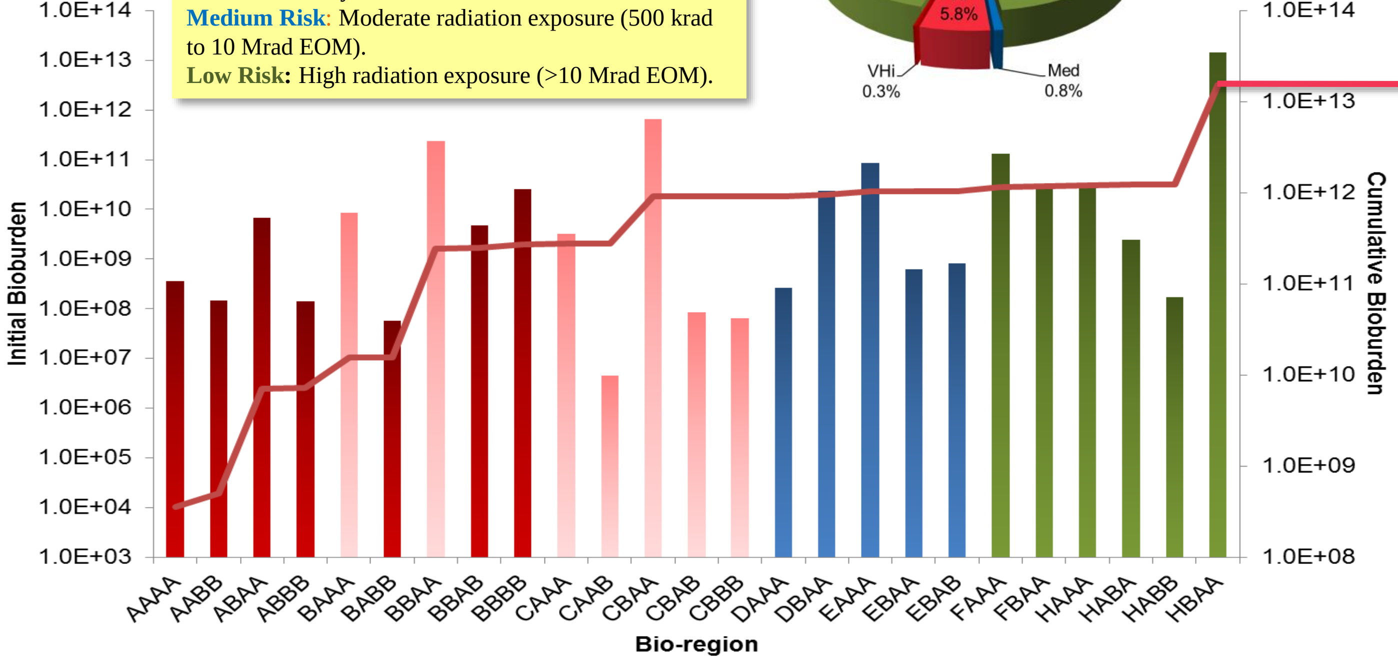


Europa Clipper Probability Model

Initial Bioburden Seed[1] & Bio-region Risk

Very High Risk: Very low radiation exposure (<50 krad EOM) & hermetically sealed. Group 4 to Group 1 organism conversion unlikely.
High Risk: Low radiation exposure (<500 krad EOM), not hermetically sealed. Group 4 to Group 1 organism conversion likely.
Medium Risk: Moderate radiation exposure (500 krad to 10 Mrad EOM).
Low Risk: High radiation exposure (>10 Mrad EOM).





Initial Bioburden estimate :

$N_0 = 1.5 \times 10^{13}$

- Group 1: 98%
- Group 2: 2%
- Group 3: 0.002%
- Group 4: 0.1%

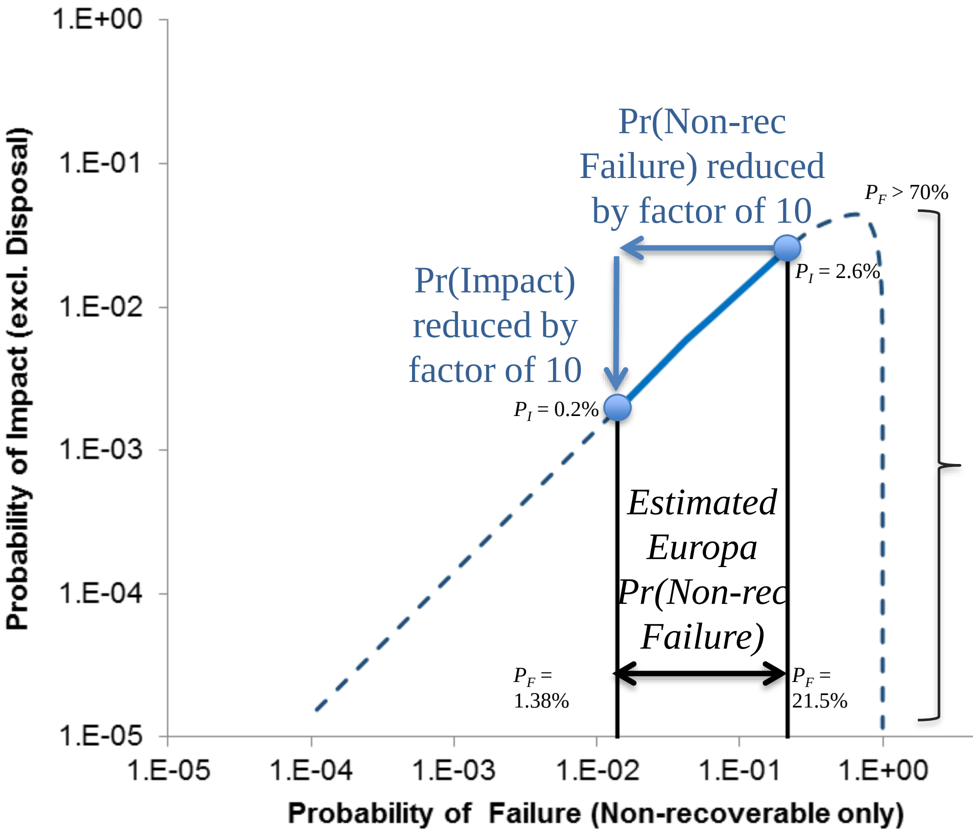
Lowest percentage, but most radiation resistant (and there are still lots of them)!

[1] *chart is representative of a cleanroom bioburden population (including manufacturing process microbe reduction); current project plan is to do further microbial reduction*

The range of Europa Clipper failure probabilities bounds Pr(Impact) between 10^{-1} and 10^{-3}

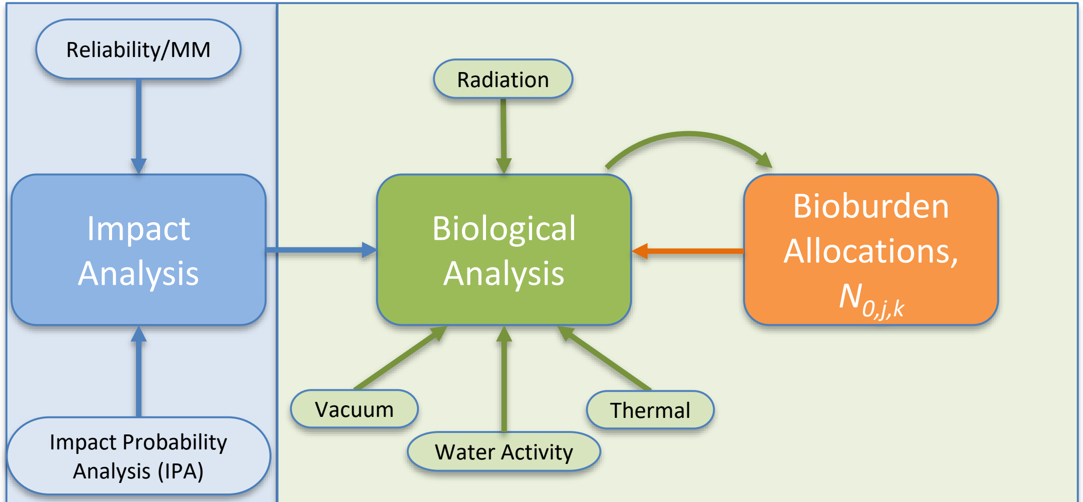
Addresses Non-Recoverable failures only

Mission	P_F
SMAP (@PDR, 3yr tour)	11.9%
MSL (CDR, 1.9yrs post-landing)	33%
JUNO (@LRD, 14 mo tour)	5.04%
Cassini (extrapolated 3.5 more yrs)	3.6%
Europa est (SRR, 3.5 yr tour)[1]	1.38%-21.5%



Note: If the chances of a non-recoverable failure get high enough, it becomes so unlikely that Clipper makes its much beyond JOI that impact is avoided.

Mathematical Model – Network Diagram



$$P_C = \sum_{n=1}^{N} \Pr\left(I_n\right) \left[1 - \frac{1}{M_n} \sum_{m=1}^{M_n} \prod_{j=1}^{J} \prod_{k=1}^{4} \left(1 - s_{j,k,m,n}\right)^{N_{0,j,k}} \right]$$

Calculates probability of impact, considering recoverable and non-recoverable failures

Applies lethality factors by bio-region (j) and organism Group (k) and develops feasible bio-burden count at launch by bio-region.

Mathematical Model – Biological Analysis

Radiation

Survival Rate for Group *k* Organisms w.r.t. to Radiation

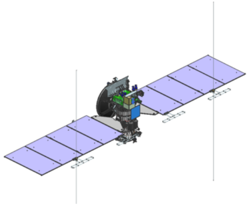
TID scaling from 100 mil Al (Si) to Bio-region *j*

*Lower bound of bio-region used for TID

TID at Impact from IPA (GRID2p) x (Estimated* TID at EOM for Bio-region *j* / 15F10 Tour TID by EOM for an Si target inside 100mil Al sphere) x Factor to convert TID on Si target to TID on a water target = TID at Impact for Bio-region *j*

Radiation Bio-regions* (krad shown is estimated TID by EOM)	Flight System Equipment
A: < 50 krad	Hardware within mini-vault or other areas with heavy local shielding (e.g. sensors, detectors, specialized EEE parts, suite of RF electronic boxes)
B: ≥ 50 krad & < 150 krad	Hardware within the vault (e.g. avionics, PME electronics)
C: ≥ 150 krad & < 500 krad	Shielded or self-shielded hardware, internal or external to spacecraft (e.g. regions of propulsion module, under vault, portions of harness)
D: ≥ 500 krad & < 1 Mrad	e.g. Tank interior, several valves, portions of harness
E: ≥ 1 Mrad & < 5 Mrad	e.g. External surfaces of prop tanks, some instrument hardware
F: ≥ 5 Mrad & < 10 Mrad	e.g. inside of solar panels, PCA/PIA, inside of HGA, much of structure
G: ≥ 10 Mrad & < 16 Mrad	Hardware just under MLI
H: ≥ 16 Mrad	First layer of MLI and all external s/c surfaces

Si Target inside a 100 mil Al Sphere



Bio-regions on Europa Spacecraft

*Lower bound of bio-region used for TID scaling

- 15F10 tour TID is 2.85MRad at EOM; factor used to convert TID relative to Si into TID relative to water is 1.3 (30% more TID relative to water)

Foundational Analysis

Reliability Analysis: non-recoverable failures

$\Pr(I_n)$

Spacecraft Hardware Failure

Ops-induced Failure

MM-induced Failure

Based on SMA historical data

0 to 5 failures (JPL/APL) planetary mission failures

- depending on inclusion of extended mission, JPL-managed, Landers

Europa design-based (APL)

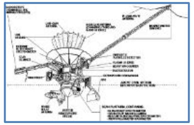
1.4%-11.3% (excluding solar array)

Reliability Analysis: recoverable failures

$\Pr(I_n)$

Cassini

# Safing events post-SOI	Mean Recovery Time
2; or 2/146 months	9 hours



Galileo

# Safing events post-JOI	Mean Recovery Time
15; or 15/93 months	25 hours

Impact Analysis: IPA

$\Pr(I_n)$

- Impact with Io
- Impact with Europa
- Impact with Ganymede
- Impact with Callisto
- Entry into Jupiter
- Escape from Jupiter
- Reach sterilization TID
- Remain in orbit

P(Impact Trajectory|Failure) for each maneuver

Estimation of Probability of Outcome Given Failure
Tour: 15F10-S22
Maneuver: G4-CU
Final time: Year 2400

Outcome	μ (%)	σ (%)	μ_{95} (%)	
Jupiter entry	0.00	0.00	0.00	0.00
Jupiter escape	0.04	0.01	0.01	0.07
Impact with Io	2.54	0.11	2.32	2.76
Impact with Europa	14.65	0.26	14.13	15.16
Impact with Ganymede	25.28	0.32	24.66	25.90
Impact with Callisto	7.20	0.18	6.85	7.55
Reached final time	50.29	0.36	49.59	50.99

TID at time of impact

GRID2p model TID approximation at time of impact under 100 mil Al (relative to Si)

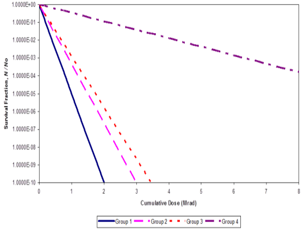
Biological Analysis: lethality factors

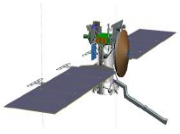
$(1-s_{j,k,m,n})^{N_{0,j,k}}$

1) Cold Temperatures +Lack of water activity

2) Exposure to vacuum of space

3) Radiation





Bio-regions

Group	Definition
1	Radiation sensitive non-spore forming bacteria
2	Radiation sensitive spore forming bacteria
3	Radiation resistant spore-forming bacteria
4	Radiation resistant non-spore forming bacteria

Reliability Analysis: Non-recoverable Failures

*Assumes FPP and DPs are followed similar to historical JPL missions

Spacecraft Hardware Failure

Ops-induced Failure

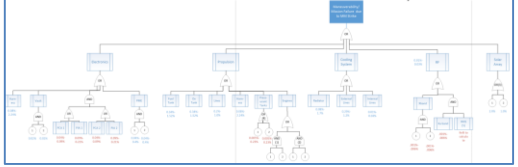
Approach: Historical Analysis (based on SMA database) using Bayesian Methods

	Spacecraft Hardware Failure*	Ops-induced Failure
# Historical Failures	• 0 JPL or APL-built outer Planetary mission failures • 1 to 3 mission failures if extended mission and JPL-managed missions (including landers) are examined	• JPL CMD file error-triggered failure (MGS) • 1 JPL other ops-induced failure (MCO)
Failure probability- prime mission **(failure rate)**	1.38%-11.16% (λ=0.004 to λ=0.034 per yr)	0.76%-3.72% (λ=0.002 to λ=0.011 per yr)

MM-induced Failure

Approach: considers current design redundancy + solar array using APL analysis

MM Fault Tree with Redundancy



MM Failure probability range (for prime mission): 1.4% to 11.3%

Non-recoverable Failure: catastrophic failure affecting maneuverability

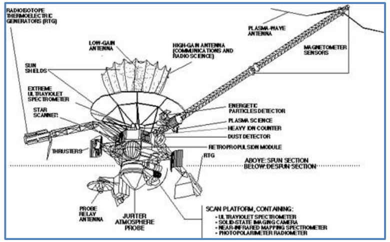
Reliability Analysis: Recoverable Failures (and recovery time)

- Approach: examine Cassini and Galileo historical records to understand causes of safing events, applicability to Europa, and respective recovery times
- Results:

Cassini

# Safing events post-SOI	Mean Maneuverability Recovery Time	Mean Science Recovery Time
2; or 2/146 months	9 hours (each recovery was limited by light time for 3 roundtrip command cycles)	13 days

Galileo



# Safing events post-JOI	Mean Maneuverability Recovery Time	Mean Science Recovery Time
15; or 15/93 months	25 hours	3.1 days

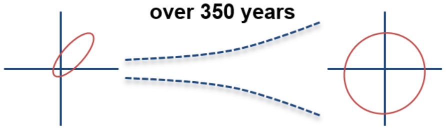
Recoverable Failure: fault affecting maneuverability that is recoverable if given enough time prior to impact

Europa RQ104.048: When a fault occurs during the Approach Maneuver that could result in the Flight System being on an impact trajectory, the spacecraft shall, without ground interaction, configure itself to a maneuver-capable state within 32 hours of the nominal end of the planned Approach Maneuver.

Europa RQ104.049: When an anomalous Europa approach maneuver places the Flight System on an impact trajectory with Europa, the Project System shall plan and execute an avoidance maneuver within 48 hours of the planned Approach maneuver.

Impact Analysis: IPA

- The mission design simulation, IPA, uses the 15F10 trajectory to produce:
  - A probability of impacting of Europa (and other icy bodies) over 350 years, given a failure occurs prior to maneuver *n*
  - TID at time of impact
  - *Velocity, angle, and surface impact coordinates*



- **Impact with Io**
- **Impact with Europa**
- **Impact with Ganymede**
- **Impact with Callisto**
- **Entry into Jupiter**
- **Escape from Jupiter**
- **Reach sterilization TID**
- **Remain in orbit**

Two key output, produced by IPA, are currently utilized:

P(Impact Trajectory|Failure) for each maneuver, n

Estimation of Probability of Outcome Given Failure
Tour: 15F10-S22
Maneuver: G4-CU
Final time: Year 2400

Outcome	**μ (%)**	**σ (%)**	**μ_{95} (%)**	
Jupiter entry	0.00	0.00	0.00	0.00
Jupiter escape	0.04	0.01	0.01	0.07
Impact with Io	2.54	0.11	2.32	2.76
Impact with Europa	14.65	0.26	14.13	15.16
Impact with Ganymede	25.28	0.32	24.66	25.90
Impact with Callisto	7.20	0.18	6.85	7.55
Reached final time	50.29	0.36	49.59	50.99

TID at time of impact

GRID2p model TID approximation at time of impact under 100 mil Al (relative to Si)

Biological Analysis

- In order to account for unique properties of microbes by species, it is critical to transform organism *Types* into disjoint *Groups*

TYPE	DEFINITION	POPULATION FRACTION
A	Culturable using the NASA Standard Assay TSA plating technique (NASA, pending)	100%
B	Spore-forming bacteria	2% of A
C	Radiation resistant spores, with ≥ 10% survival above 0.8 Mrad	~ 0.1% of B
D	Radiation resistant non-spore-forming bacteria, with ≥ 10% survival above 4.0 Mrad	~ 0.1% of A

Source: Space Studies Board Report, 2000

GROUP	TYPE	DEFINITION
1	**=A-B-D**	Radiation sensitive non-spore forming bacteria
2	**=B-C**	Radiation sensitive spore forming bacteria
3	**=C**	Radiation resistant spore-forming bacteria
4	**=D**	Radiation resistant non-spore forming bacteria

Source: JUNO mission

- Lethality factors considered to date:

Factor	Threshold Value
Exposure to ionizing radiation	Sterilization assumed at 8.5MRad across all surfaces
Exposure to space during cruise	If in sealed, non-vented region of s/c then not exposed to space environment
Exposure to water activity	a_w<0.2
Exposure to extreme cold	<-33 degrees C

Source: NPR, JUNO mission, Aparecida, K. (2012), MEPAG (2014)

The combination of these factors causes metabolic changes only; there is no lethality credit taken for presence of these factors

Factor	Threshold Value
Impact time at temperature	Sterilization assumed if temperature >500 C for >0.5 s on all surfaces

Source: NPR, JUNO mission

Biological Analysis (con't)

Exposure to space during Cruise

P(Group 1 org survives)=0.1;
P(Group 4 org survives)=0.5

$$\sum_{n=1}^{N} \Pr(I_n)\left[1-\frac{1}{\mathrm{M}_n}\sum_{m=1}^{\mathrm{M}_n}\prod_{j=1}^{J}\prod_{k=1}^{4}\left(1-s_{j,k,m,n}\right)^{N_{0,j,k}}\right]$$

Hermetically sealed hardware?

No

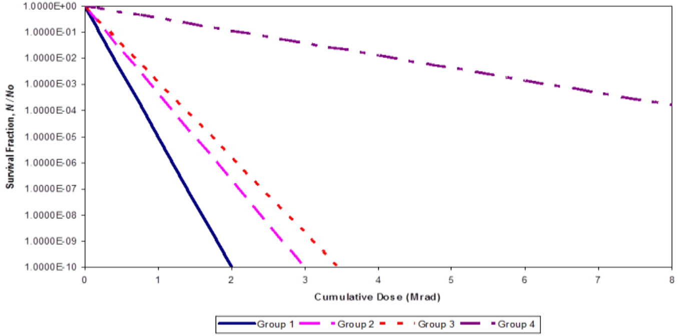
A portion of Group 1 & 4 organisms die when exposed to the environment of space

P(Group 1 org survives)= e $^{-(11.5D)}$
P(Group 2 org survives)= e $^{-(7.7D)}$
P(Group 3 org survives)= e $^{-(6.7D)}$
P(Group 4 org survives)= e $^{-(1.1D)}$

D= TID scaled to bio-region j

Source (JUNO mission): SSB, 2000

Ionizing Radiation Response



Source (JUNO mission): Group 1 & 2: Kohlhase, 2004; Group 3: Urgiles, E, 2007; Group 4: Li, S. W., et al., 2007

Metabolic Activity

Water Activity <0.2

+

Does hardware reach temp < -33 C?

Yes

Group 4 organisms become more radiation sensitive because they lose their ability to repair, similar to to Group 1 organisms

Assumed Biobuden Densities
Cleanroom only case

Bioburden Density	Value
Surface burden density: uncontrolled manufacturing	1 x 10^5 spores/m^2
Surface burden density: ISO 8 (Class 100,000) clean room with normal controls	1 x 10^4 spores/m^2
Surface burden density: ISO 8 (Class 100,000) clean room with stringent controls	1 x 10^3 spores/m^2
Surface burden density: ISO 7 (Class 10,000) clean room with normal controls	5 x 10^2 spores/m^2
Surface burden density: ISO 7 (Class 10,000) clean room with stringent controls	50 spores/m^2
Surface burden density: alcohol-wiped surface protected from recontamination	300 spores/m^2
Surface burden density: precision-cleaned surface protected from recontamination	600 spores/m^2
Surface burden density: electronic board under conformal coat (assembled at JPL) with more stringent controls	1000 spores/m^2
Encapsulated burden density: in non-metallic materials	130 spores/cm^{-3}
Encapsulated burden density: specific to electronic piece parts	150 spores/cm^{-3}
Encapsulated burden density: specific to non-electronic non-metallic materials	30 spores/cm^{-3}

Input Product Maturity Assessment

Key

- Will evolve with Project design maturity
- May require further biological research
- Reasonable maturity

Maneuverability Failure

<u>Non-recoverable Failure Rate</u>
-MM: *Source* APL MMOD analysis
-H/W, Ops induced: *Source* SMA historical db

<u>Recoverable Failure Rate</u>
-Cassini, Galileo Analysis: *Source* ISA db, historical records

<u>Recovery Rate</u>
-Cassini, Galileo Analysis: *Source* ISA db, historical records

Impact Probability Analysis (IPA)

<u>Probability on impact trajectory| maneuver failure</u>
Source Mission Design

<u>Time to impact</u>
Source Mission Design

<u>TID at impact</u>
Source Mission Design, GRID 2p

PP Statistical Model

Biological Factors

<u>Lethality Curves, Factors</u>
-TID curves: *Source* various cited papers, JUNO mission
-Vacuum desiccation: *Source* Space Studies Board Report
-Lack of water + low Temp effects: *Source NPR, MEPAG*

<u>Organism Groups</u>
Source Space Studies Board, JUNO mission

<u>Sterilization Determination</u>
-Sterilization determination: *Source* NPR, PP team

<u>Lethality Factor Bins</u>
Source initial transport analysis and PP team support

<u>Bio-region Development (incl Equipment List)</u>
Source SMEs, HW owners, PP team/PPEL, modeling team
Source System MEL supplemented with hw owner input

<u>N_0 seed</u>
Source PPEL mapping to bio-regions

Failure and Impact probabilities can only take us so far

Addresses Non-Recoverable failures only

Mission	P_F
SMAP (@PDR, 3yr tour)	11.9%
MSL (CDR, 1.9yrs post-landing)	33%
JUNO (@LRD, 14 mo tour)	5.04%
Cassini (extrapolated 3.5 more yrs)	3.6%
Europa est (SRR, 3.5 yr tour)	1.38%-21.5%

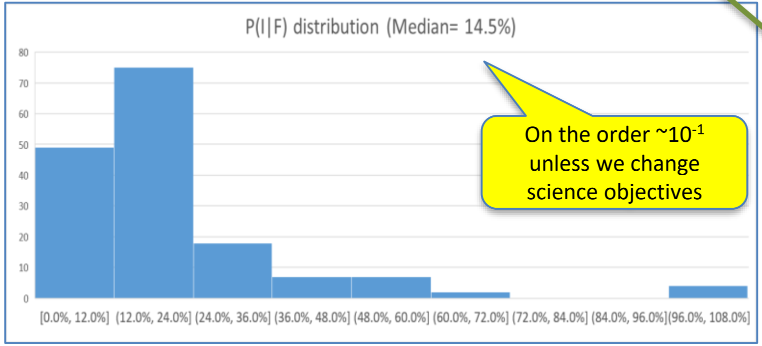
On the order of ~10^{-1} to 10^{-2}

This product is the Probability of Impact, P_I

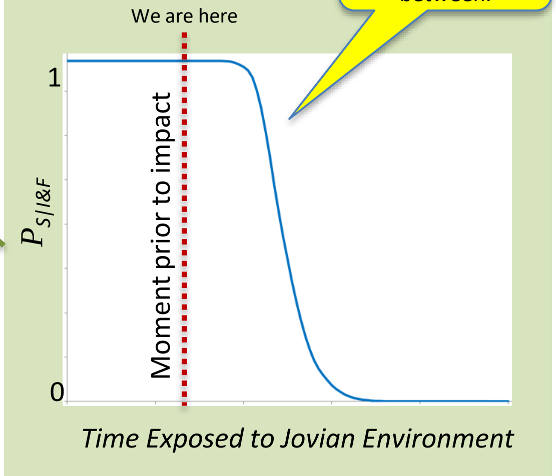
Probability at least one organism survives given Europa impact

P_F and $P_{I|F}$ contribute a magnitude ~$\mathbf{10^{-2}}$ **to** $\mathbf{10^{-3}}$ to the P_C calculation (excluding 'recoverable' failures)

$$P_C = \boxed{\boldsymbol{P_F\, P_{I|F}}}\,\boxed{P_{S|I\&F}}$$



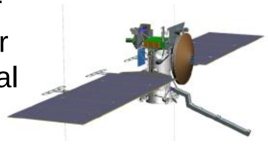
Either 1 or 0; not much in between.



Bio-region Overview

What is a bio-region?

- Spatial region of the spacecraft where organisms respond in a similar manner to factors affecting their viability.
  - A bio-region is not necessarily a contiguous region
  - Bio-regions are disjoint from one another
  - Within a bio-region, bioburden may either be in an encapsulated, mated, or an external surface of a component

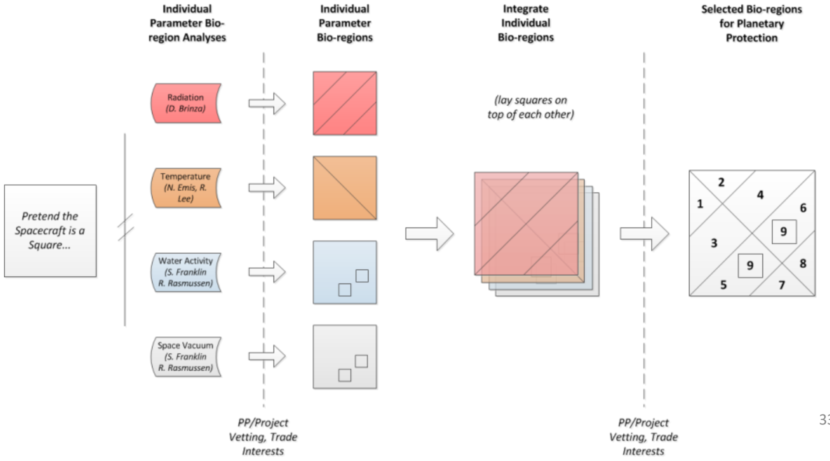


Why are they needed?

- Without segregating areas of the spacecraft based on organism lethality exposure, an accurate result for N_0 cannot be obtained
- As the number of bio-regions increases, the fidelity of the N_0 result increases
  - It is possible to treat every component in the MEL or even every surface of every component as a bioregion if necessary
  - The current number of bio-regions is 25.

How were they constructed?

- Derived from the current MEL
- Performed biological research to find driving parameters of organism viability (temperature, radiation, water activity, space vacuum)
- Met with discipline and subsystem experts to map the MEL to bio-regions
- Bio-region definitions are commensurate with current maturity of the flight system design and will evolve
- Bio-region information is integrated into the PPEL



Bio-region Definitions

1) Ionizing Radiation

Radiation bio-regions group spacecraft zones in a manner that considers radiation transport across the spacecraft

- Thresholds values used to define each bio-region are the estimated radiation dose as of End of Prime Mission.
- Some equipment is partially shielded; where that was known, the

Radiation Bio-regions (krad shown is estimated TID by End of Prime Mission)[5]	Flight System Equipment (preliminary)
A: < 50 krad	Hardware within mini-vault or other areas with heavy local shielding (e.g. sensors, detectors, specialized EEE parts, suite of RF electronic boxes)
B: ≥ 50 krad & < 150 krad	Hardware within the vault (e.g. avionics, PME electronics)
C: ≥ 150 krad & < 500 krad	Shielded or self-shielded hardware, internal or external to spacecraft (e.g. regions of propulsion module, under vault, portions of harness)
D: ≥ 500 krad & < 1 Mrad	e.g. Tank interior, several valves, portions of harness
E: ≥ 1 Mrad & < 5 Mrad	e.g. External surfaces of prop tanks, some instrument hardware
F: ≥ 5 Mrad & < 10 Mrad	e.g. inside of solar panels, PCA/PIA, inside of HGA, much of structure
G: ≥ 10 Mrad & < 16 Mrad	Hardware just under MLI
H: ≥ 16 Mrad	First layer of MLI and all external s/c surfaces

2) Cold Temperatures

Thermal extremes across the spacecraft were assessed against the current plan for thermal control.

- Temperature threshold of -33° C defines a bioregion

Temperature Bio-regions	Flight System Equipment (preliminary)
A: Reaches -33° C.	Not a thermally controlled region of flight system (e.g. most telecom H/W, Solar Arrays, MLI, most S/C structure, harnessing, radiator, heaters, HRS (excl. pump)
B: May not or will not reach -33° C	Thermally controlled or well-insulated regions of the flight system (e.g. most instruments, Power SS (except SA cells), Avionics, Frontier Radio, Amplifiers, Vault Structure, Reaction Wheels, Prop Module)

Bio-region Definitions (con’t)

3) Water Activity

Water Activity was considered across the spacecraft.

- The bio-regions is defined based on whether or not the hardware experiences a water activity <0.2
- Often this depends on sealing, venting, or purging of particular areas of the spacecraft or hardware

Water Activity Bio-regions	Flight System Equipment (preliminary)
A: Water Activity < 0.2	Dry areas, typically not sealed (includes certain areas that are sealed but are dried through other means; e.g. purging, in-ops heat decontamination)
B: Water Activity ≥ 0.2	Typically hermetically sealed equipment

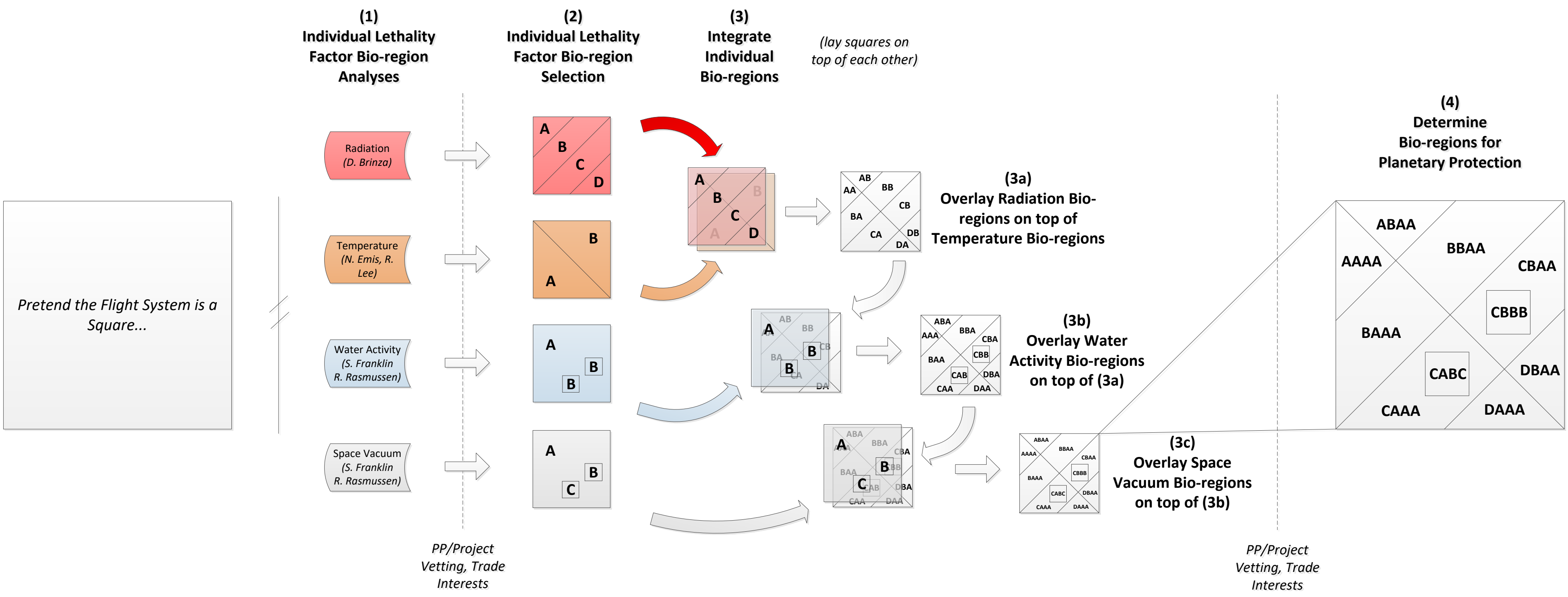
4) Desiccation

Exposure to the environment of space can incite microbial desiccation in some species.

- Exposure does not occur when an area or part is sealed without venting

Space Vacuum Bio-regions	Flight System Equipment (preliminary)
A: Exposed to space vacuum	Typically non-hermetically sealed, vented areas
B: Not exposed to space vacuum	Hermetically sealed such that organisms are not exposed to the space vacuum (e.g. IMU, battery cells)

Bio-region Development Illustration



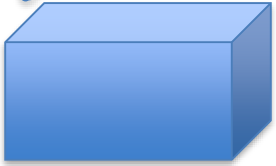
*A given bio-region does not need to be a contiguous space; one bio-region can consist of disjoint areas of the s/c.

Developed a Bio-region – PPEL Interface

BIO-REGION DEVELOPMENT

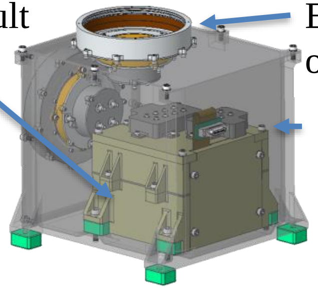
Started with the MEL…

50-16,000+ krad by EOM



…which gave very top-level perspective…

50 krad by EOM in vault

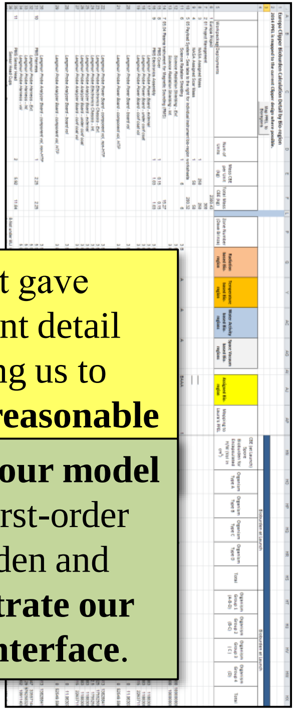


16+ Mrad by EOM on outer surface

500 krad by EOM for harnessing

…until we met with hardware leads…

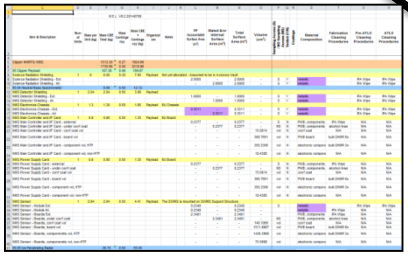
INTEGRATED BIO-REGIONS & PPEL



…that gave important detail enabling us to **discover reasonable**

BIOBURDEN ALLOCATION

Started with the Europa PPEL…



…which we mapped to our bio-regions…

…bringing with it additional detail required by NPR*

…to **seed our model** with a first-order bioburden and **demonstrate our PPEL interface**.

*NPR 8020.12D, A.17: Total Bioburden. Total of exposed, mated, and encapsulated microbial burden.

Alternative Brief Mathematical Derivation

$$\boldsymbol{P_C} = \sum_{\boldsymbol{n}=1}^{\boldsymbol{N}} \Pr\left(\boldsymbol{S} \cap \boldsymbol{I_n}\right)$$

by the Law of Total Probability; $\boldsymbol{S}$ = the event that 1 or more organisms survive long enough to contaminate Europa.

$$= \sum_{\boldsymbol{n}=1}^{\boldsymbol{N}} \Pr\left(\boldsymbol{I_n}\right) \Pr\left(\boldsymbol{S} \mid \boldsymbol{I_n}\right)$$

by definition of conditional probability

$$= \sum_{\boldsymbol{n}=1}^{\boldsymbol{N}} \Pr\left(\boldsymbol{I_n}\right) \left[1 - \Pr\left(\boldsymbol{S^C} \mid \boldsymbol{I_n}\right)\right]$$

$\boldsymbol{S^C}$ = the event that no organism survives long enough to contaminate Europa = $\boldsymbol{S}$ does not occur

$$= \sum_{\boldsymbol{n}=1}^{\boldsymbol{N}} \Pr\left(\boldsymbol{I_n}\right) \left[1 - \sum_{\boldsymbol{m}=1}^{\mathrm{M_n}} \Pr\left(\boldsymbol{S^C} \mid \boldsymbol{I_n}, \text{on trajectory } \boldsymbol{m}\right) \Pr(\text{on trajectory } \boldsymbol{m} \mid \boldsymbol{I_n})\right]$$

$$= \sum_{\boldsymbol{n}=1}^{\boldsymbol{N}} \Pr\left(\boldsymbol{I_n}\right) \left[1 - \frac{1}{\mathrm{M_n}} \sum_{\boldsymbol{m}=1}^{\mathrm{M_n}} \prod_{\boldsymbol{j}=1}^{\boldsymbol{J}} \prod_{\boldsymbol{k}=1}^{4} \left(1 - \boldsymbol{s_{j,k,m,n}}\right)^{\boldsymbol{N_{0,j,k}}}\right]$$

by applying the binomial model to the number of surviving organisms, given impact occurs on trajectory $\boldsymbol{m}$.

Note difference between capital “S” (event 1 or more organisms survive) and lower case “s”.(probability an individual organism survives)